Predictability of Particle Trajectories in the Ocean

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LONG-TERM GOALS

The long term goal of this project is to determine optimal sampling strategies for drifting observing systems, such as buoys and gliders, in order to enhance prediction of particle motion in the ocean, with potential applications to ecological, search and rescue, floating mine problems, and design of real-time observing systems.

OBJECTIVES

Our main objective is to develop Lagrangian techniques to improve our fundamental understanding of turbulent transport phenomena in the ocean. The objectives of the project serve the ONR thrust area of adaptive sampling and Lagrangian tracing. Another aspect of the research focuses on a better understanding of the nature of mesoscale and submesoscale turbulent processes, which is relevant to ONR thrust area on submesoscale variability associated with fronts, turbulence and mixing.

APPROACH

The work is based primarily on the analysis of output from coastal and ocean circulation models, as well as data from drifters and VHF radars deployed for real-time experiments. We also develop and/or employ Lagrangian models and techniques as needed.

WORK COMPLETED

1) Publication of a paper estimating relative dispersion in the Ligurian Sea from drifters launched in the 2008 MREA (Marine Rapid Environmental Assessment) trials and on the basis of NCOM operationally run in that region (Schroeder et al., 2011).

2) Participation in the 2010 MREA (denoted LIDEX2010 and REP2010) trials organized by NURC/NATO (led by Jacopo Chiggiato) and Italian CNR. Our main role was to design a

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multi-scale drifter launch strategy and take part in the decision about where to launch the drifters.

3) Completion of a paper in which we have done extensive work trying to incorporate the effects of submesoscale motions on relative dispersion. The paper has undergone a positive review and was recently revised (Haza et al., 2011).

RESULTS

The project is not received any funding over the past year and we have completed our work under no-cost extension. Only a brief summary is provided here.

Introduction: Ocean model fields are being routinely used for forecasting the spreading of pollutants, oil spills, and for biogeochemical transport. Recent observations and advances in our understanding of multi-scale ocean processes indicate that while transport in the mesoscale range is controlled by the structure and slow temporal variability of long-lasting mesoscale jets and eddies, there is an explosion of flow instabilities in the submesoscale range that appear to have a significant impact on transport at their own scale of motion. While satellite altimeter assimilation results in approximately realistic representation of the mesoscale coherent features in ocean models, submesoscale motions require much more extensive data sets and numerical computations. As such, submesoscale processes remain quite challenging to capture/resolve deterministically. Even though the dynamical system methods to compute Lagrangian Coherent Structures (LCS) are ideally suited for the mesoscale range, their applicability is reduced due to the emergence of smaller-scale, complex, rapidly-evolving fields that are hard to observe and resolve explicitly.On the other hand, it has not been straightforward to incorporate mesoscale features in Lagrangian subgridscale (LSGS) models, but these statistical methods appear more suitable as flows become increasingly more turbulent. We pose the following questions:

1) How can we combine LCS and LSGS methods in mesoscale eddy-resolving OGCMs in places which exhibit, in space and/or in time, strong submesoscale features, in order to attain and analyze realistic relative dispersion in the multi-scale setting of the ocean?

2) Is it possible to adapt an LSGS model which would not only improve the scale dependent relative dispersion statistics, but also maintain the Lagrangian transport barriers of the mesoscale eddy field set by the ocean model?

Three Lagrangian subgridscale (LSGS) models that had been developed on the basis of statistical considerations are used in order to tackle the multi-scale ocean transport problem. We put forward a hybrid approach, in which the modeled transport is based on the deterministic LCS over the mesoscale range and the statistical LSGS over the submesoscale range.

We study transport in the Gulf Stream region, which exhibits clear indications of strong submesoscale activity from both models and observations. We consider two HYCOM solutions at different resolutions, namely with $1/12^o$ and $1/48^o$ horizontal meshes respectively, and we use a measure of relative dispersion, the scale-dependent finite scale Lyapunov exponent, as our main metric to diagnose their differences in terms of transport. The particular focus of this study is on correcting the underestimation of submesoscale dispersion regime in the $1/12^o$ solution, while the $1/48^o$ resolution case and an existing observational data set indicate a trend toward much higher dispersion. We study

the LSGS models and characterize their parameter ranges that yield an improvement in multi-scale relative dispersion.

Motivation: The FSLE maps of two HYCOM numerical simulations of the Gulf Stream with grid spacings of $1/12^o$ and $1/48^o$ are shown in Fig. 1. The lower resolution simulation displays a web of dispersion extrema corresponding to the transport barriers of the mesoscale circulation (namely, the Gulf Stream meanders and eddies). Since the grid spacing is about one fourth the radius of deformation, the model cannot really resolve the submesoscale motions. However, the $1/48^o$ configuration can resolve features down to about 4 km, and the submesoscale flow instabilities are evidenced by an explosion of relatively short-lived, complex web of FSLE extrema. Direct comparison of scale-dependent FSLE $\lambda(\delta)$ indicates that the enhanced strain by such submesoscale features contributes to an increase in at the smallest separation scale δ=2 km, denoted λ_{max}, by a factor of two (Fig. 2).

We can assume that this increase reflects the scale-dependent relative dispersion of in-situ drifters, although it is not clear how many intermediate regimes exist between the transition to mesoscale dispersion and the exponential regime, characterized by a plateau in the $\lambda(\delta)$ plot, since there has been very few observations taylored to sample the submesoscale dispersion. Lumpkin and Elipod (2010) found in the Gulf Stream region three distinct regimes below the radius of deformation: a Richardson regime down to 10 km, a ballistic regime down to 2 km, and indication of an exponential regime between 1 and 2 km with λ_{max} more than ten times higher than in HYCOM $1/48^o$.

Approach: Three LSGS models have been tested. The LSGS-1 and LSGS-2 are versions of so-called random walk and random flight models discussed in detail by Griffa (1996) and used quite often in biological transport applications. The LSGS-3 is a quite original model that we had developed a few years ago, but it is relatively unknown and it has never been used in studies of relative dispersion before. Two metrics have been used for evaluation; scale-dependent FSLE, which is a measure of mixing based on two-particle statistics, and second moment of particle positions, which quantifies dispersion of the particle cloud around their center of mass.

Performance of LSGS models: Results shown in Fig. 3 clearly indicate that both LSGS-1 (random walk, similar results are obtained for the random flight model) and LSGS-3 models can be used to introduce significant corrections for the submesoscale relative dispersion. We find that LSGS-3 has several advantages over LSGS-1,2. First, by design, LSGS-1,2 introduce turbulent velocity fluctuations everywhere, while LSGS-3 acts to enhance (or reduce) the strain rate only in region associated with the LCS, as diagnosed by high FSLE. The LCS are quite robust since they are associated with mesoscale features, and cannot be easily eliminated subgridscale perturbations. But apparently, it is not physical to add perturbations independently of the underlying flow field. Second, we also find that LSGS-3 can quite readily match the cloud spreading metric from the higher resolution simulation (Fig. 4).

IMPACT/APPLICATIONS

The investigation of the predictability of particle motion is an important area of study, with a number of potential practical applications at very different scales, including searching for persons or valuable objects lost at sea, tracking floating mines, ecological problems such as the spreading of pollutants or fish larvae, design of observing systems and navigation algorithms.

RELATED PROJECTS

Lagrangian Turbulence and Transport in Semi-Enclosed Basins and Coastal Regions, PI: A. Griffa, N00014-05-1-0094.

Statistical and Stochastic Problems in Ocean Modeling and Prediction, PI: L. Piterbarg, N00014-99-1-0042.

Optimal Deployment of Drifting Acoustic Sensors: Sensitivity of Lagrangian Boundaries to Model Uncertainty, PI: A. Poje, N00014-04-1-0192.

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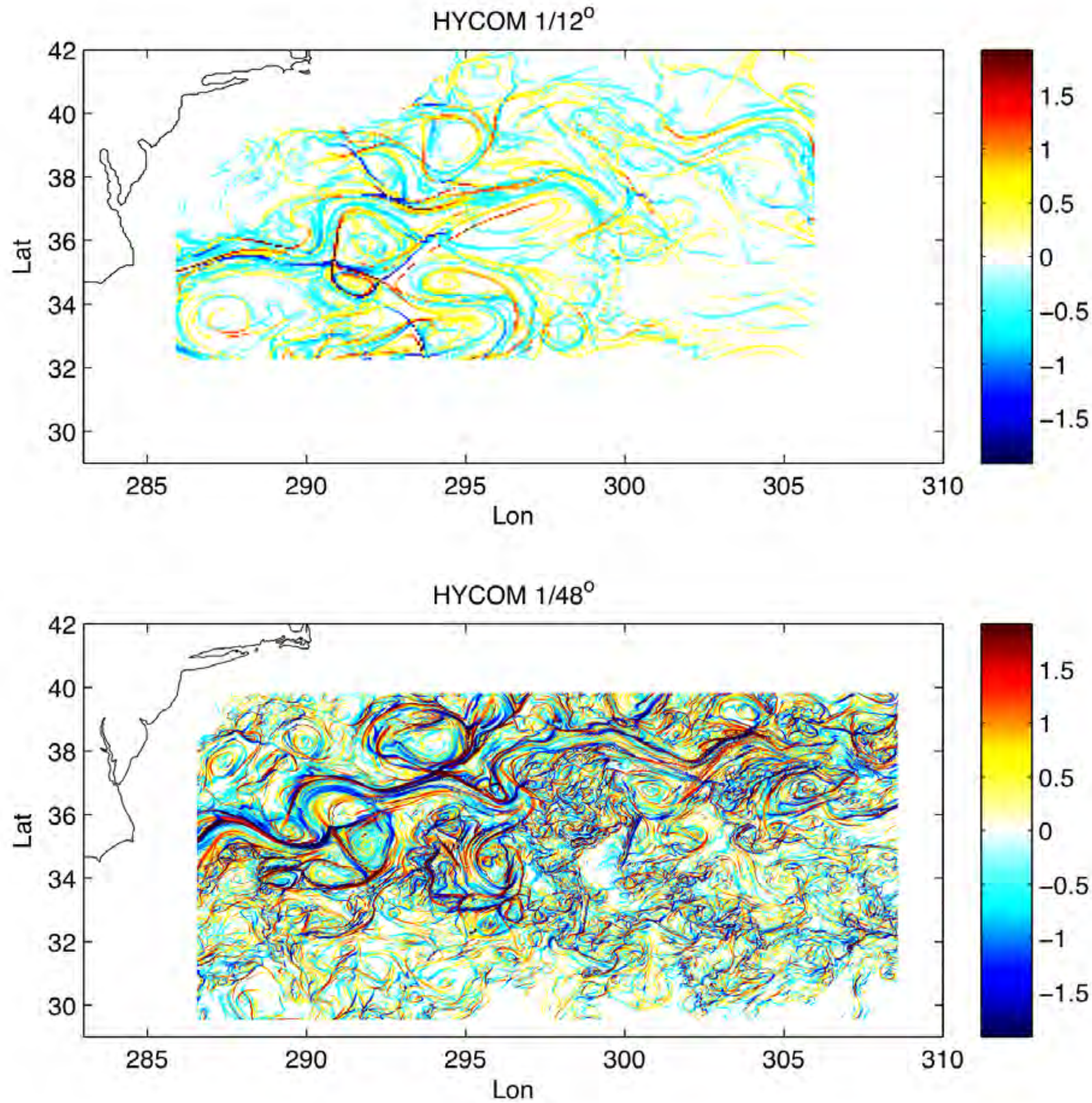

Fig. 1: FSLE branches from 1/12^o (upper panel) and 1/48^o (lower panel) HYCOM simulations in the Gulf Stream region. Note the rich submesoscale field in the higher resolution case. The color panels indicate FSLE in 1/days. Blue colors show in-flowing/stable LCS from forward in time, and red colors out-flowing/unstable LCS from backward in time particle advection.

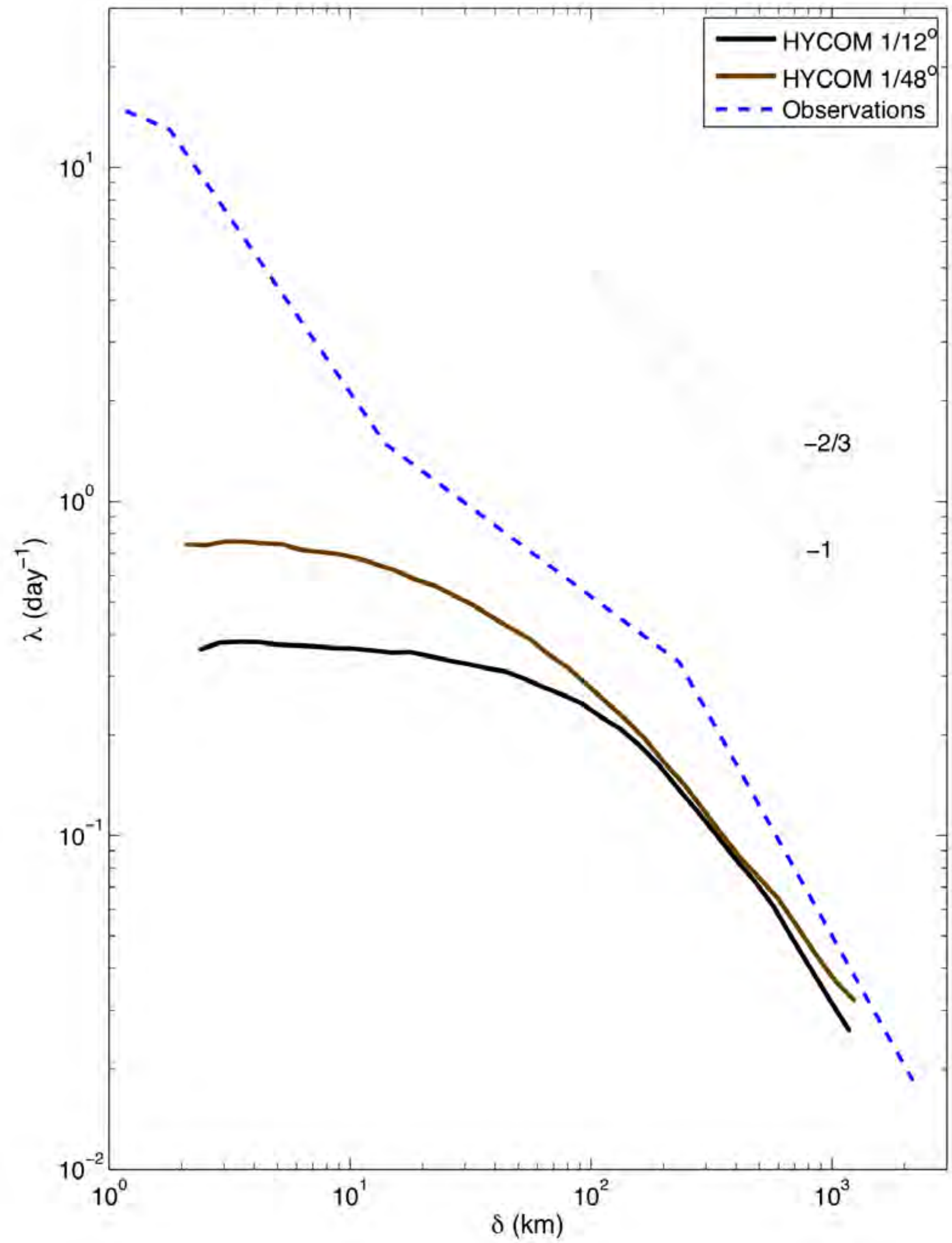

Fig. 2: Scale-dependent FSLE $\lambda(\delta)$ from HYCOM solutions with horizontal mesh spacings 1/12^o (black) and 1/48^o (brown). The observational results from Lumpkin and Elipod (2010) is reproduced and shown by the dashed line. Ballistic (λ~δ^{-1}) and Richardson (λ~$\delta^{-2/3}$) regimes are indicated.

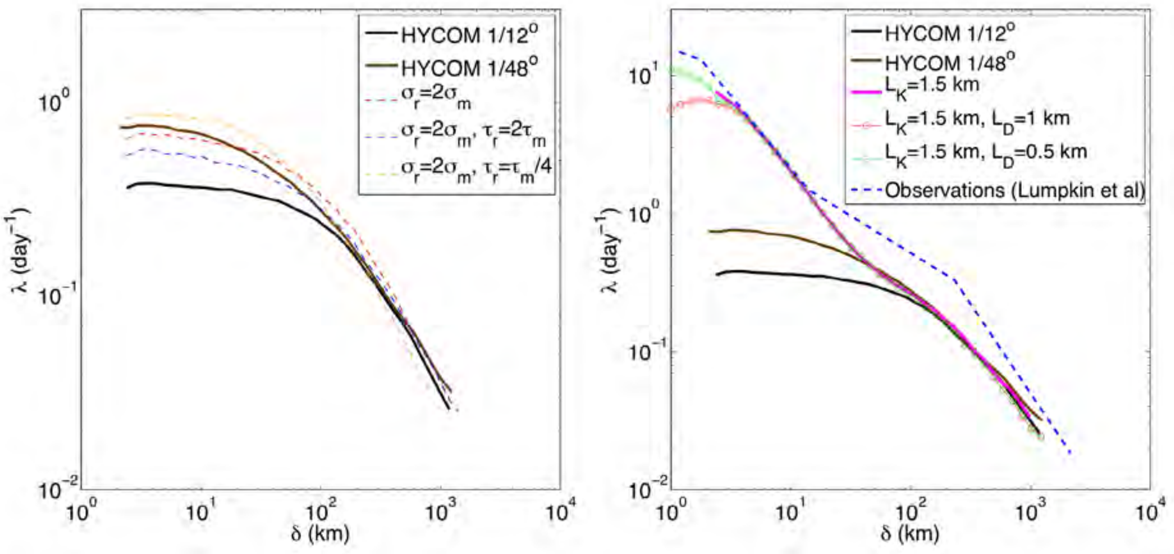

Fig. 3: (left panel) Approximation of the FSLE curves from 1/48^o HYCOM (brown) using LSGS-3 with various parameter combinations in 1/12^o HYCOM (black). (Right panel) Approximation of the observed FSLE curve (Lumpkin and Elipod, 2010) using LSGS-1 model in in 1/12^o HYCOM.

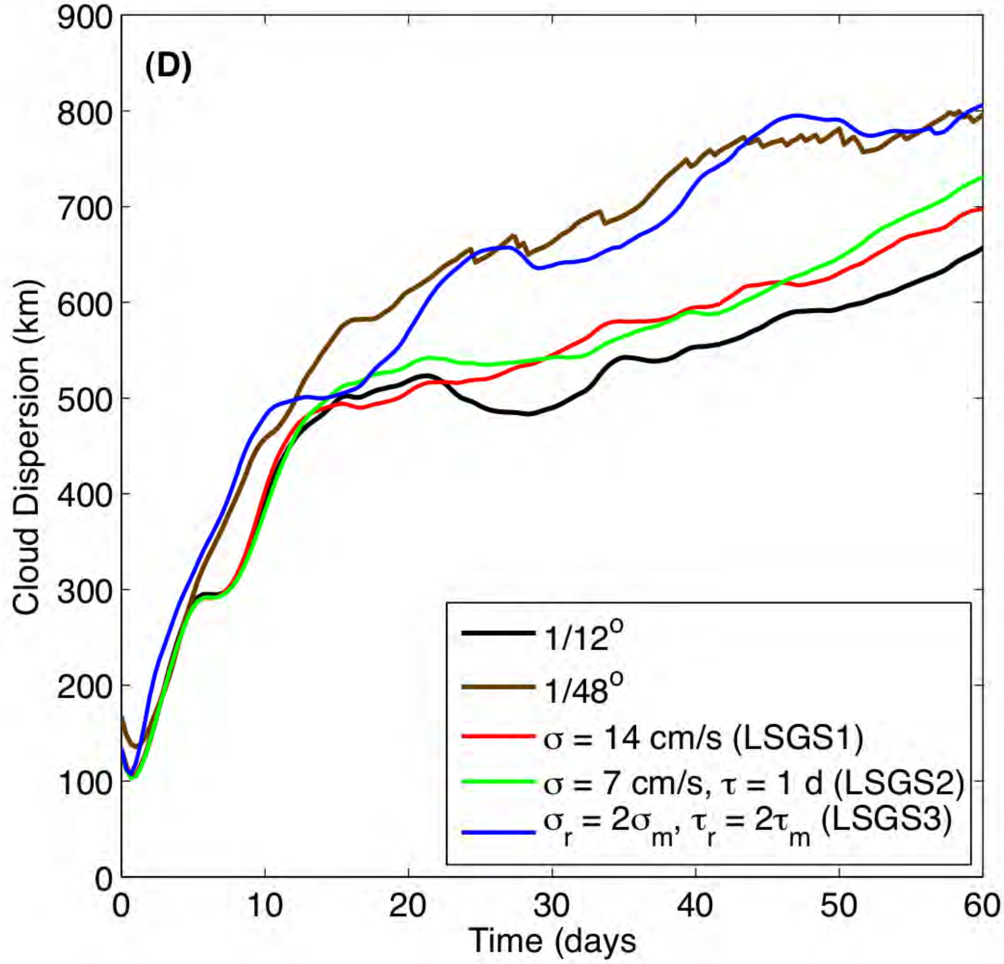

Fig. 4: Comparison of second moment of particle position variance (cloud spreading) from 1/12^o (black) and 1/48^o (brown) HYCOM output and those from LGSG-1, LGSGS-2 and LSGS-3. Note that only LSGS-3 leads to a similar cloud spreading as in the submesoscale-containing 1/48^o simulation.